Simulation of thermal stabilization of bases under engineering structures in permafrost zone

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Simulation of Thermal Stabilization of Bases under Engineering Structures in Permafrost Zone

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Abstract. Constructions on permafrost have to be ensured with reliability of the foundation, which, under the influence of various heat fluxes and annual freezing (thawing) of the soil, may get stressed, that leads to destruction of the foundation and the engineering structure itself. To assess the thermal impact of engineering structures on the ground, a computer simulation of the construction pads is used. Thermal stabilization of the soil is considered to be carried out due to freezing with the help of seasonally operating cooling devices for some time prior to the beginning of construction, or placing on site various technical systems that are sources of heat. The results of numerical calculations illustrating the effectiveness of preliminary thermal stabilization of the soil under the base of the engineering structure are presented.

Introduction

The main feature of permafrost soils is that the particles are firmly cemented by ice structures, and the mechanical properties essentially depend on temperature. In addition, such soils are unstable and significantly influenced by both changes in climatic conditions and human intervention[1]. In Russia, permafrost has a widespread, especially in the northern regions, but the type of distribution, temperature and the depth vary considerably.

In permafrost soils, it is possible to distinguish two main zones: first zone is an accumulation layer, in which the soil temperature is constantly changing during the year (Active Layer Thickness or ALT), second zone is relatively stable and has the same temperature over many years [2]. In addition, in permafrost areas the territories to be subject of development and constructing are possible to be divided into two groups according to permafrost conditions: territories where the seasonal freezing-thawing layer (ALT) merges with the deep permafrost soils and the territories where the ALT is isolated from the base. [3, 4]

Permafrost soils are used as a foundation by two principles [2, 5].

Active principle: The permafrost soils of the base are used in a melted or thawing state, that call to modify foundation material conditions prior to construction. This is a common method of construction on sites, where ALT does not merge with permafrost soils. Structurally, it is expressed in the laying of foundations in the thawed layer of soil over the permafrost. Preliminary thawing of permafrost prior to construction has not found wide application so far.

Passive principle: the foundations used in the frozen state, keeping it during construction and for the operation period [6, 7]. Structurally, it is expressed in the laying of foundations in the permafrost and the building support with a crawl space or other cooling systems. This method ensures the reliability and longevity of structures, if it is accompanying by the elimination of thermal effects on the base soils of nearby buildings and structures. In the passive principle soil conservation in the frozen state is ensured by the arrangement of various cooling measures:

- cold crawl space;
- cold ground floor;
- using cooling pipes, ducts or ventilated foundations;
- seasonally operating cooling devices using (SCDs);
- other measures of elimination or reducing the thermal impact of the structure on frozen grounds.

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Failures of building foundations constructed according to the passive method, which are attributed to changes in permafrost, very often do not directly relate to changes of air and permafrost temperature. Such foundations failures are not caused by permafrost warming but by climatic effects on foundations material in the active layer and in a crawl space, unaccounted for thermal stresses, and low freeze-thaw resistance of concrete in piles. Recently, the crawl spaces on piles were a most common engineering solution to eliminate the thermal impact of structures on permafrost. However, this principle of construction leads to a significant increase in the cost of foundations up to 60% of the total cost and has limited capacity. In addition to the economic inefficiencies of it does not match the criteria of maintainability and controllability in the case external thermal effects on permafrost soils. Although, indeed, the avoidance of the direct contact between the construction as a heat source and the frozen base is a method of reducing interaction [6].

(a) (b)

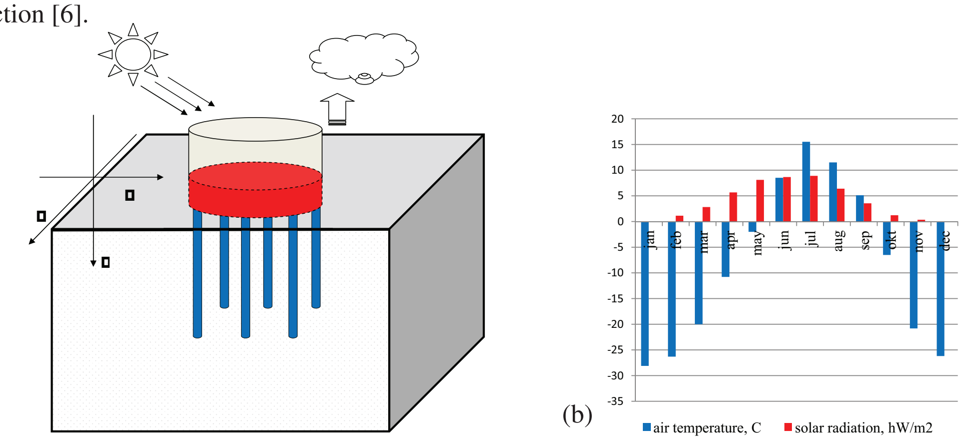


FIGURE 1. A basic scheme of simulated area (a), basic climatic prameters: air temperature (° C) and solar radiation, hW/m^2(b).

Numerous building failures in permafrost regions are related to changes in permafrost due to poor design, and to poor maintenance of buildings, which are more powerful factors than the natural change in permafrost temperature. As long as the mean annual temperature remains below 0°C, means of permafrost protection without artificial refrigeration could be applied. On summer, as a result of positive temperatures and solar radiation effect, there is a seasonal thawing of the upper layer, on winter there is a reverse freezing process. Thawing of ice-saturated rocks due to warming or various technogenic impacts could be accompanied by subsidence of the earth's surface and the development of thermokarst, leading to destruction of various engineering structures [8, 9].

Studying thermal fields on the surface of the soil from underground pipelines in view to determine the damages [10, 11], it was found that the solar radiation has a great influence on the formation of thermal fields in the upper layer of the soil. Therefore, in studying non-stationary fields propagation in the soil from various technical systems used in the northern oil and gas fields [12, 13], solar radiation was also taken into account.

With high-temperature permafrost soils, the different SCDs systems have a widespread application. SCDs are quite effective when used in the system and complex planning permafrost areas development [12]. For example, with the help of a cooling system, it is possible to lower the temperature of the base, turning the soils from unstable to frozen solid during 1–2 years and to improve the reliability of the base [1].

In this paper, several approaches to the organization of the foundation for high-temperature frozen soil are compared. Using a developed mathematical model, a series of computations is carried out, which makes it possible to evaluate effectiveness of soil conservation measures in the frozen state under foundation of a heated construction.

Model of Heat Distribution in Permafrost

The basic human influences on permafrost consists of a combination of disturbance of the structure of the upper layers of the soil and thermal impact of different technical systems. To simulate the processes of heat distribution in permafrost soil a three-dimensional diffusivity equation with non-uniform coefficients including localized heat of phase transition is considered. Following [14, 15, 16] this approach allows to solve the problem of Stefan type, without the explicit separation of the phase transition in 3D area (Figure 1a). The equation has the form

$$\rho\Big(c_\nu(T) + k\delta(T - T^*)\Big)\frac{\partial T}{\partial t} = \nabla\,(\lambda(T)\Delta T), \tag{1}$$

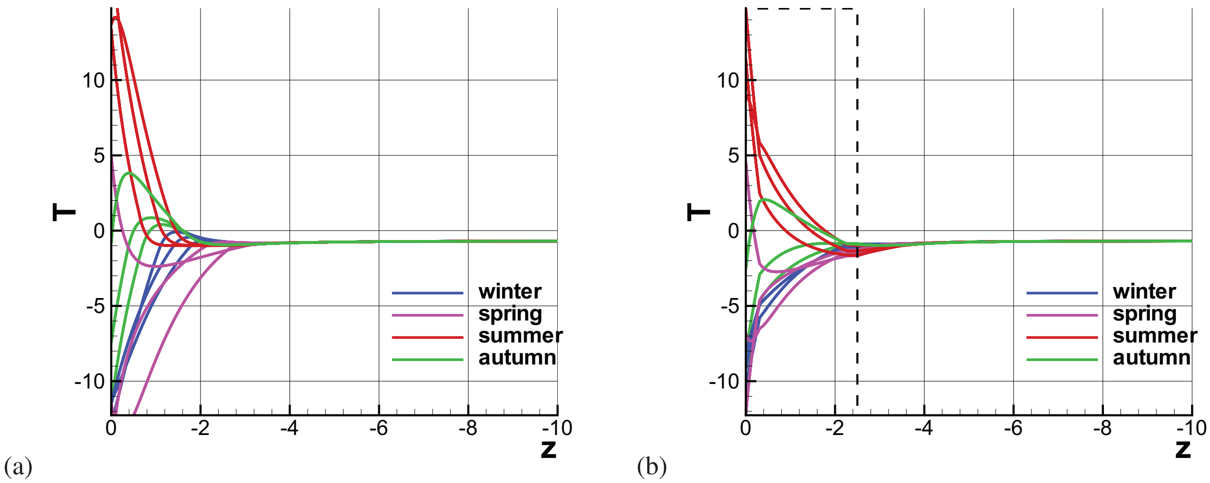


FIGURE 2. Temperature profiles in the soil: uncovered (a), with a riprap (b).

with initial condition

$$T(0, x, y, z) = T_0(x, y, z). \tag{2}$$

Here ρ is density $[kg/m^3]$, T^* is temperature of phase transition $[K]$,

$$c_v(T) = \begin{cases} c_1(x, y, z), & T < T^*, \\ c_2(x, y, z), & T > T^*, \end{cases} \text{ is specific heat [J/kg K],}$$

$$\lambda(T) = \begin{cases} \lambda_1(x, y, z), & T < T^*, \\ \lambda_2(x, y, z), & T > T^*, \end{cases} \text{ is thermal conductivity coefficient [W/m K],}$$

$k = k(x, y, z)$ is specific heat of phase transition, δ is Dirac delta function.

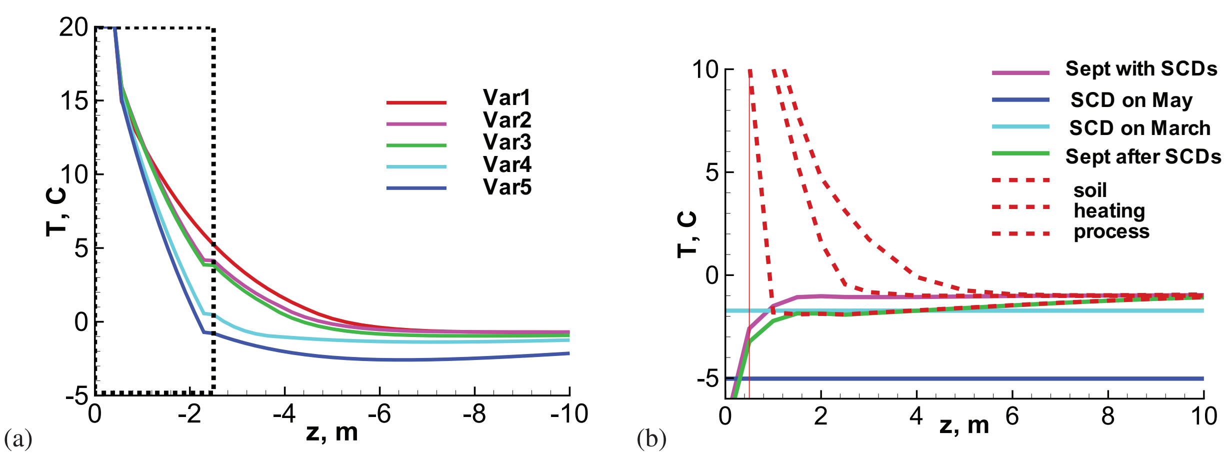


FIGURE 3. Temperature profiles under the container: on September (a), on different fazes of SCD functioning (b).

Balance of heat fluxes at the surface $z = 0$ defines the corresponding nonlinear boundary conditions

$$\gamma q + b(T_{air} - T(x, y, 0, t)) = \varepsilon\sigma(T^4(x, y, 0, t) - T_{air}^4) + \lambda \frac{\partial T(x, y, 0, t)}{\partial z}. \tag{3}$$

To determine the parameters in boundary condition (3), an iterative algorithm is developed that takes into account the geographic coordinates of the area, lithology of soil and other features of the considered location [7, 14, 17]. In Figures 1a and 1b the basic thermal units and the monly average data, respectively, for the considered area. The permafrost temperature lower than the area of influence of seasonal changes (lower than 10 meters) is -0.7°C.

In Figures 2a and 2b the temperatures in near-surface layer of soil for different months are shown for the uncoated soil and the soil with a 2.5m riprap, respectively. The basic thermal parameters of the soil are in the following: thermal conductivity is 1.82 and 1.58 W/(m K), volumetric heat is 2130 and 3140 kJ/(m^3 K) for frozen and melted soil, respectively; volumetric heat of phase transition is $1.384 \cdot 10^5$ kJ/(m^3 K).

Stabilization of soil is primarily due to the restriction of seasonal effects of changes in air temperature and solar radiation intensity. To do this, as a rule, multi-layer ripraps are used. Figure 2(right) presents temperature profiles for different months with 2.5m of riprap: 0.3m of concrete slab, 2m of sand, 0.2m of foam. The temperature variation range in the near-surface layer of the soil is much less than in uncoated soil, the soil under the riprap is kept longer in a stable frozen state.

Let consider n SCDs which are included in Ω. In Figure 1 the surfaces of these objects are tubes $\Omega_i(x, y, z)$, $i = 0, \ldots, n$. The index $i = 0$ corresponds to the warm container. These surfaces suppose to be inner boundaries with the conditions

$$T\Big|_{\Omega_i} = T_i(t), \quad i = 0, \ldots, n. \tag{4}$$

The computational domain is a three-dimensional box Ω, where x and y axes are parallel to the ground surface and the z axis is directed downward. We assume that the size of the box Ω is defined by positive numbers L_x, L_y, L_z: $-L_x \le x \le L_x$, $-L_y \le y \le L_y$, $-L_z \le z \le 0$.

At the boundaries of the domain the boundary conditions are given

$$\frac{\partial T}{\partial x}\Big|_{x=\pm L_x} = \frac{\partial T}{\partial y}\Big|_{y=\pm L_y} = 0, \quad \frac{\partial T}{\partial z}\Big|_{z=-L_z} = 0. \tag{5}$$

On the base of ideas in [15, 16] a finite difference method is used with splitting by the spatial variables in three-dimensional domain to solve the problem. We construct an orthogonal grid, uniform, or condensing near the ground surface or to the surfaces of internal boundaries (Ω_i, Figure 1).

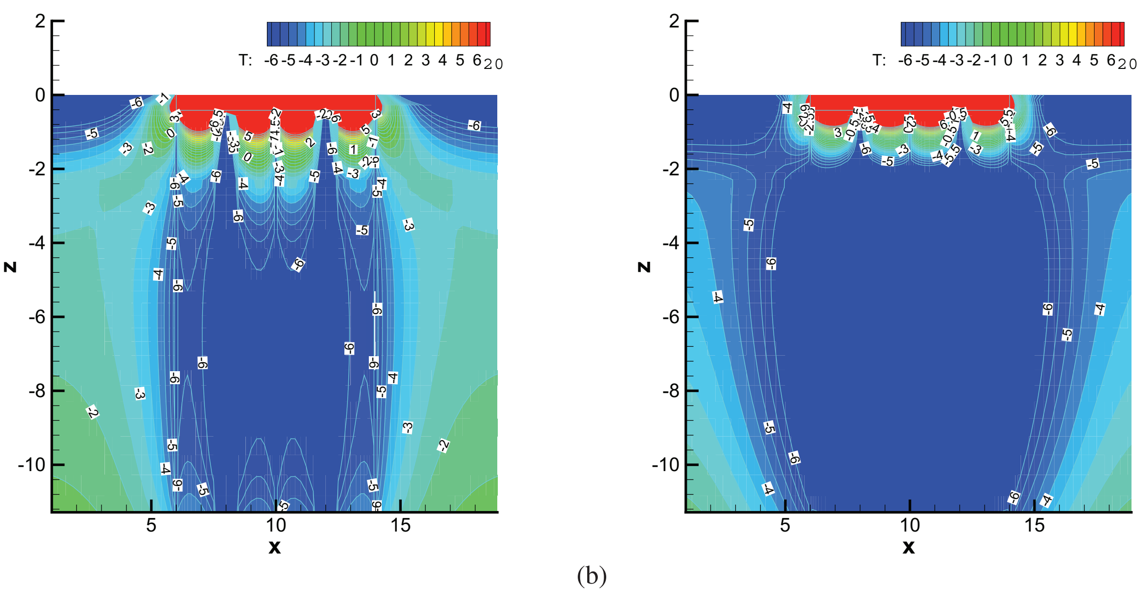


FIGURE 4. Temperature fields under the container in a vertical plane: in December (a), in March (b).

TABLE 1. Basic annual climatic parameters.

	Var. 1	Var. 2	Var. 3	Var. 4	Var. 5
2,5 m riprap	-	+	+	+	+
2 years prelim. freezing	-	-	9 SCDs 4m dist	+	+
SCD action under constr.	-	-	-	9 SCDs 4m dist	25 SCDs 2m dist

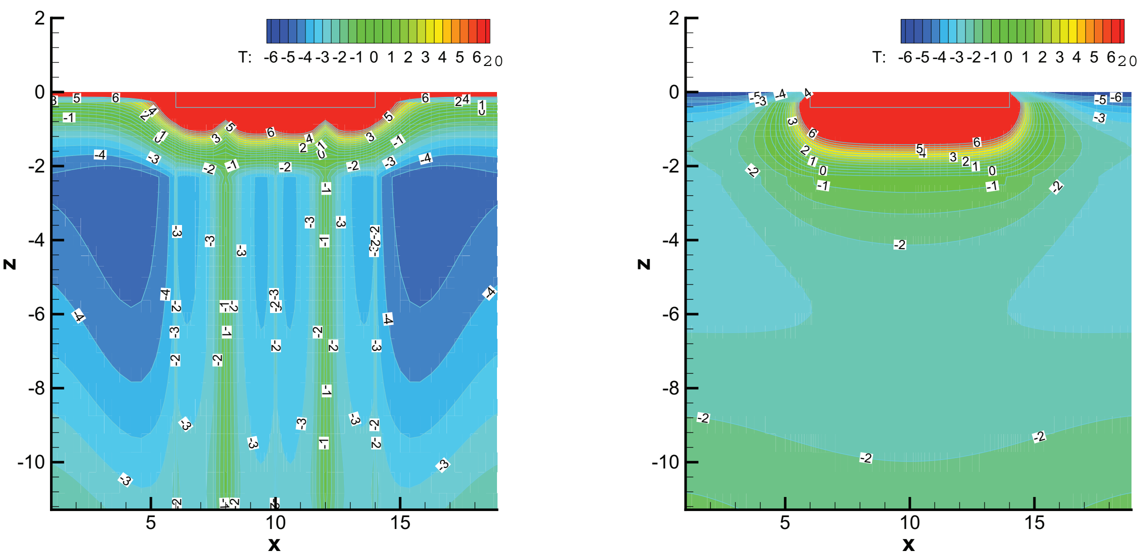
The original equation for each spatial direction is approximated by a locally additive implicit scheme, and to solve a system of linear differential algebraic equations the combination of the sweep and Newton method is used. Solvability of the same difference problems approximating (1)–(5) is proved in [18].

Numerical results

Let consider a system of several SCDs located in frozen soil (Figure 1), serving as a background for the warm container with the inner temperature 20°C. the container is placed in the center of the area. The SCDs are located in the nodes of a rectangular mesh at the distance of d [m] from each other. A number of SCDs in the mesh will be denoted by n, for example, in Figure 1 $n = 3 \times 2$, where 3 and 2 are numbers of SCDs along the axis x and y, respectively.

Size of the computational area are L_x=L_y=L_z=20m, SCD's deep iz 11.5m, diameter is 0.057 m. The basic soil temperature is -0.7°C. Numerical grid sizes had varied from 91x91x51 to 191x191x151, time step is 24 hours. The basic climatic parameters are presented in Figure 1b.

In Table 1 the variants of stabilization of the base of the container ane considered. the basic options are the following: using the 2,5m of riprap, preliminary freezing of the base by SCDs during 2 years, continuous SCDs functioning.



(a) (b)

FIGURE 5. Temperature fields under the container in a vertical plane: in June (a), in September (b).

In Figure 3a the temperature profiles are presented for the variants. Variant 1 is worst one, Variant 5 is the best, when the conservation principle continuously applied. Figure 3b illustrates the SCD temperature for different months, and the thawing processes in the soil when the SCDs are not used in background of the following container exploitation. Without the additional cooling of the base it is not possible to conserve the permafrost foundation.

Figures 4 and 5 show the thermal fields under the container in the vertical xz section of the soil for Variant 5. December and March illustrates the soil freezing under SCDs operation and June and September shows the thermal trace of SCDs effect after the season the soil warmed up.

Conclusion

To analyze the effectiveness of the foundation on permafrost soils a mathematical model is developed and numerical calculations are carried out. Preliminary freezing of upper layers of the soil artificially created the conditions of the passive principle, i.e. the melt base substrates transform into hard frozen and further remain in this state. Preliminary freezing without support in the future is ineffective. So, the complex and comprehensive use of ripraps and insulations allow to optimize the SCDs system application for thermal stabilization of permafrost under constructions.

Acknowledgments

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